

FBW DESIGN CHOICES

Anthony A.Lambregts
FAA National Resource Specialist
Advanced Controls

AGENDA

- **Motivation for FBW Design**
- **Control tasks and functions - pitch / roll / yaw**
- **Functional architecture; issues and choices**
 - **Controller type (column, wheel; sidestick)**
 - **Control Algorithms**
 - **Handling Qualities**
 - **Feel systems and backdrives**
 - **Displays**
 - **Envelope protection**
- **System implementation - Hardware/Software**
 - **Architectures**
 - **Functional reliability strategies**
- **Certification; Special Conditions**
- **Guidance materials**

MOTIVATION FOR FBW DESIGN

- **Reduction of Direct Operating Cost**
 - **Optimization airplane aerodynamic performance**
 - **aft c.g./reduced trim drag → need SAS**
 - **weight reduction - mechanical elements: cables, pulleys**
 - **maintenance of mechanical system element**
 - **reduced parts inventory**
 - **improvement and standardization of flying qualities**
 - **common type rating / reduced cross training**
- **Enhanced safety**
 - **loss of control prevention: envelope protection**
 - **speed envelope / g / bank angle protection**
 - **reduced risk extracting maximum performance**
- **Modernization, function integration flight controls & avionics**

CONTROL TASKS

Vertical plane

- **take off :**
 - **rotate and establish pitch attitude**
- **climb:**
 - **control acceleration or airspeed**
- **cruise / terminal area:**
 - **hold altitude, speed**
- **idle descend:**
 - **hold speed**
- **final approach:**
 - **track glide slope, maintain speed**
- **landing flare:**
 - **control flight path, pitch attitude**

CONTROL TASKS (cont'd)

Horizontal plane :

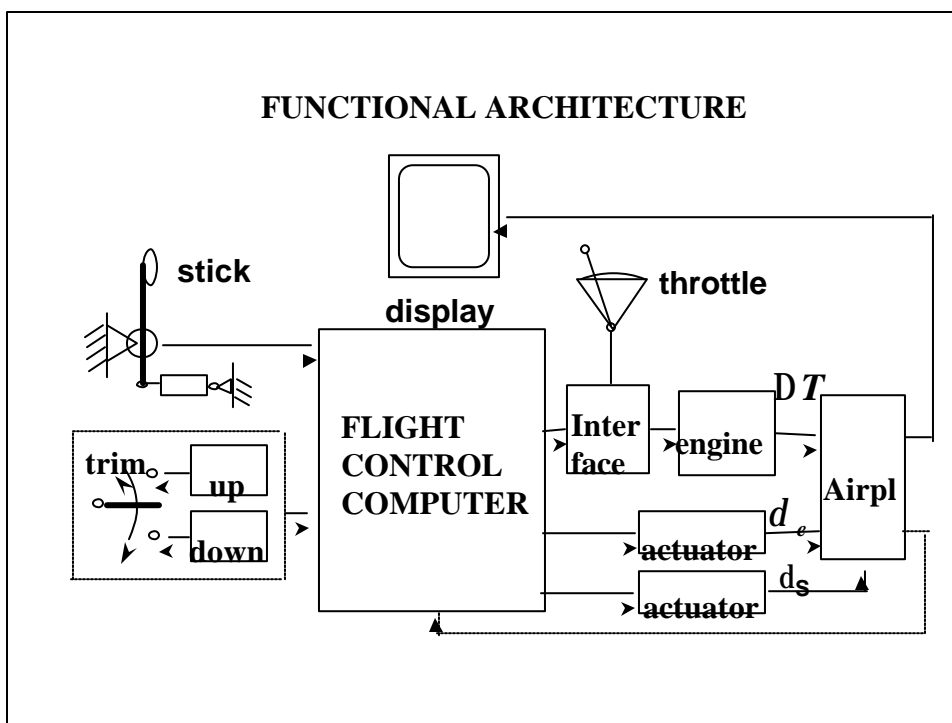
- take off/ cruise / descent / initial approach:
 - roll attitude/heading / track localizer
- final approach
 - acquire & maintain localizer
- landing:
 - decrab, maintain track

Emergency:

- windshear escape: high angle of attack
- collision avoidance: high N_z , bankangle

The major design difficulty is to achieve satisfactory handling qualities for all these tasks and flight conditions

FUNCTIONAL ARCHITECTURE



FBW DESIGN ISSUES

- **Column & Wheel versus Sidestick**
- **Passive versus *Active* feel system**
- **Control algorithm**
 - **Stability and command augmentation options (C*, C*U, etc)**
 - **Handling qualities and workload**
 - **Speed stability or equivalent safety provisions**
- **Envelope protection**
- **Mode changes for *up and away* and *takeoff/landing***
- ***Central* actuator loop closure in electronics bay, versus *remote* loop closure at actuator**
- **Manual and automatic mode integration**

FBW DESIGN OPPORTUNITIES

- **simplify operational concept**
- **simplify hardware architecture and design**
 - **shedding historically accumulated “baggage”, e.g. design features typically belonging to previous generations of technologies:**
 - **complex feel systems**
 - **column, wheel back-drive systems**
 - **stick shaker**
 - **individual actuator loop closure - Force Fight**
- **Instead of designing band aids to make it possible for the pilot live with the vagaries in the system, the FBW system should eliminate these vagaries (and band aids)**

Let the pilot get the credit, and let the computer do the work

ADDITIONAL FBW PAY OFF POTENTIAL

- **better functional integration of flight control system**
 - **unified strategy for FBW manual and automatic control**
 - **consistency between manual and automatic control**
 - **up-front integration of functions**
 - **pitch/thrust control**
 - **roll/yaw control (including rudder) - inherent**
 - **yaw damping /turn coordination**
 - *inherent thrust asymmetry compensation*
 - **improved/uniform handling qualities & safety**
 - **reduce probability of pilot error, loss of control**
 - **shorter design development /certification schedule**
 - **simpler/ generalized / reusable design & software**

FBW DESGN CONTROVERSY

- **Should classical airplane response be preserved or should system be designed to achieve “best” HQ and safety?**
- **If designing for best HQ and safety, what are implications for pilot training, multiple type rating and HQ degradation/ change in case of failure(s)**

My personal position:

- **it is futile to try and stop progress**
- **it is unwise not to take advantage of new technologies**

New technologies require lots of design lead time, extensive validation and experience to successfully avoid pitfalls

COLUMN AND WHEEL VERSUS SIDESTICK

	<u>Advantage</u>	<u>Disadvantage</u>
Column & Wheel	<ul style="list-style-type: none">• traditional• simple cross-connect	<ul style="list-style-type: none">• weight• space requir.• display viewing obstruction
Sidestick	<ul style="list-style-type: none">• weight saving• unobstructed display• space for work table	<ul style="list-style-type: none">• cross-connect difficult• possible “cross talk”• active feel difficult, but not needed

COLUMN / WHEEL / SIDESTICK SENSORS

- **FORCE input** - used in early FBW designs
 - Control Wheel Steering (pseudo FBW, e.g. B737, B747-200, DC-10, MD-11)
 - early F-16: rigid stick
 - OK for small maneuvers
 - problem: no feel of control authority limit
- **DISPLACEMENT input** - now generally used
 - tactile indication of displacement limit
 - with proper matching of authority to displacement limit and sensitivity scheduling, a simple linear feel spring suffices

FBW CONTROL ALGORITHM OPTIONS

- **None - direct surface commands, proportional to input**
- **Simple stability augmentation:**
 - **preserve “classical response”, improve HQ where needed**
 - *caution: classical does not mean best HQ, nor safest*
 - **proportional feedbacks only; no integral control terms**
 - **simple feed forward signal path**
 - **no control reference command development**
 - **no long term command tracking**
 - **“classical feel”/ trim**

FBW CONTROL ALGORITHM OPTIONS (cont’d)

- **Advanced command and stability augmentation:**
 - **achieve “most desirable” HQ and lower workload, using a variety of control design features, e.g.**
 - **control reference command**
 - **proportional + integral feedback control**
 - **multiple feed forward commands**
 - **other control control response shaping elements**
 - **reference command :attitude, vertical speed, flight path angle, airspeed, heading, track angle; developed by**
 - **integration of control input (preferred)**
 - **synchronization (prone to HQ problems)**
 - **long term command tracking**
 - **pilot in the loop only when maneuvering**
 - **unconventional trim, e.g. automatic**

ADVANCED FBW CONTROL ALGORITHMS

- **Pitch**
 - angle of attack or attitude proportional command
 - attitude rate command / attitude hold
 - n_z command / vertical speed hold
 - flight path angle rate command & FPA hold
- **Roll**
 - attitude rate command / attitude hold
 - attitude rate command / attitude hold for bankangle $> X^\circ$ & heading or track hold for bankangle $< X^\circ$
 - attitude rate command / turn radius hold
- Given sufficient know-how, all of these concepts can be made to perform well : *the devil is in the details!*

HANDLING QUALITIES

Definition: The conglomerate of characteristics and features that facilitate the execution of a specific flight control task

- required design attributes for good HQ depends on task
- control task difficulty relates to the number of integrations involved in the controlled variable
- each integration creates response delay (lag)
- each task has a finite time allotment or expectation for its completion (bandwidth requirement)
- dynamic elements in the control loop often used to shape the control response
- control harmony is achieved when the pilot can execute the task without undue stress and conscious effort

HANDLING QUALITIES (cont'd)

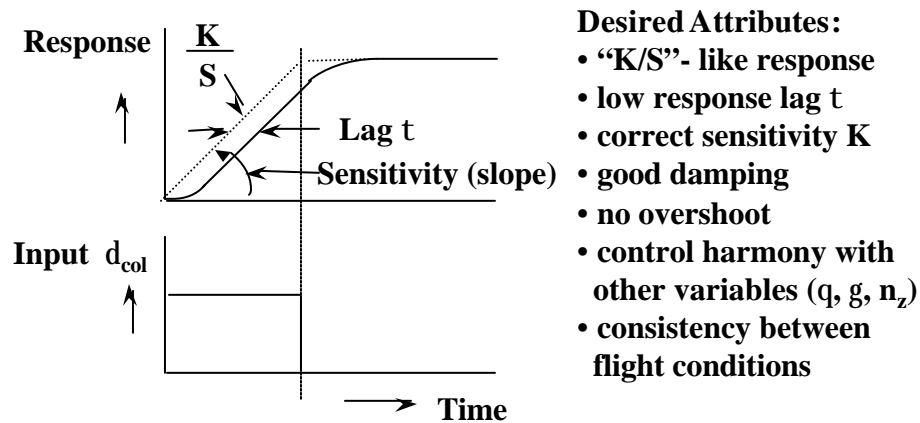
- *predictability* of the response is a major HQ attribute, facilitated by *proportionality* (linearity) of
 - controlled variable to control input
 - control force (“feel”) to control displacement
 - control display to control input
- undue time delays should be avoided, e.g. due to actuators, higher order dynamic elements in the loop
- integrator-like response of the controlled variable in “cross over” freq. range facilitates task execution $\frac{q}{d_c} = (\cdot) \frac{K}{S}$
 - example: pitch/roll attitude to stick input
 - landing flare is a notable exception: here $\frac{q}{d_c} = (\cdot) K$ is more desirable
- pilot needs suitable display to close control loop

HANDLING QUALITIES (cont'd)

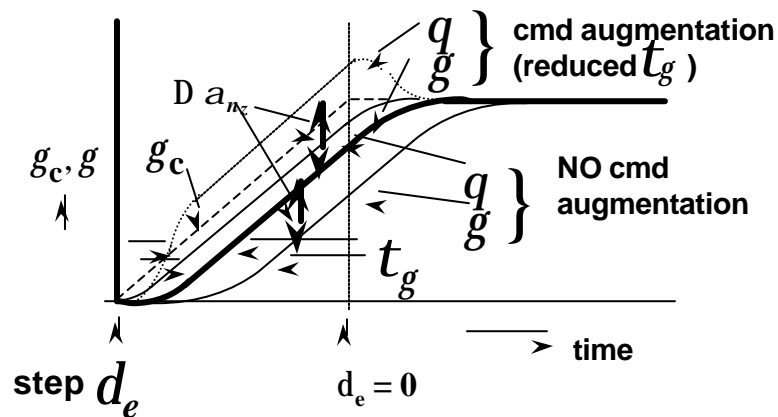
- Short Period based HQ criteria inadequate for complex tasks
- Autothrust ON/OFF strongly affects HQ
- Stability augmentation affects airplane response in turbulence
- Command augmentation & control reference affects
 - pilot’s control strategy
 - workload in turbulence, during configuration changes
 - potential for LOC during unattended operation
 - need for landing flare sub-mode (e.g. C* and C*U alg.)
- Automatic pitch trim inappropriate when
 - autothrust OFF
 - autothrust ON and thrust required exceeds thrust available *unless* envelope protection function(s) provided

FBW CONTROL

Response Attributes for good HQ



RELATIONSHIP q, g, a

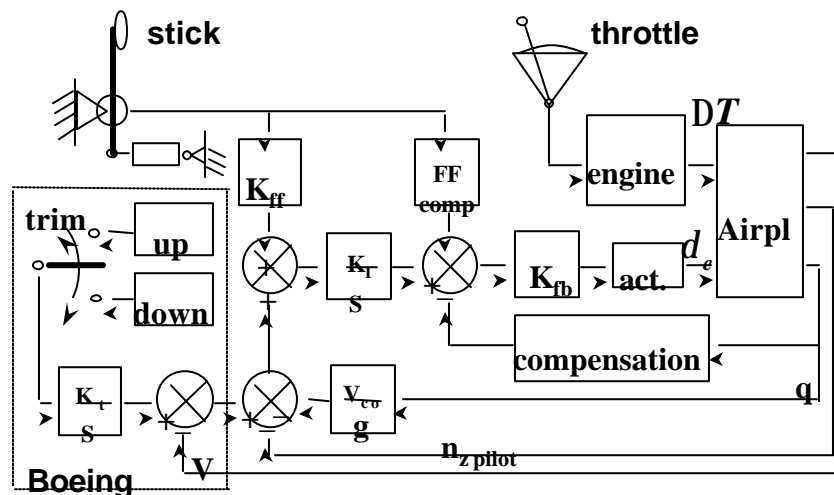


- g response lag t_g affected by cmd augmentation
- $D a_{n_z}$ determined by basic airplane, flight condition

C* CRITERION

- **Postulation: Pilot responds to blend of pitch rate and normal acceleration, with blend ratio varying with natural variation in aircraft response**
 - **Definition:** $C^* = (n_z)_{ps} + (V_{co}/g)q$
 - V_{co} = speed at which “contributions” of $(n_z)_{ps}$ and q to HQ cues are equal
 - Assumes airplane has good handling qualities when response of C^* -variable falls within certain experimentally determined envelope
- **the criterion was found to have little merit (AFFDL)**
 - $Dn_z = V \cdot \dot{FPA} / g = V \cdot q / g$, (assuming $V = \text{constant}$)
 - V_{co} has no physical meaning, no significance to pilot

BASIC C* AND C*U CONTROL ALGORITHM IMPLEMENTATION



C* ALGORITHM CHARACTERISTICS

- **C* algorithm**
 - Feedback of $\ddot{\alpha}(C^*)dt \gg \dot{h} + q$; provides path (phugoid) damping
 - \dot{h} feedback destroys speed stability
 - There is no flight path command reference, and no long term path tracking capability (autothrottle off)
 - Additional design complications not shown:
 - n_z corrections needed to avoid divergence
 - algorithm reconfiguration for Take Off & Landing
 - Certification based on *equivalent safety* obtained by speed/angle of attack envelope protection

C*U ALGORITHM CHARACTERISTICS

C*U algorithm

- U of C*U represents speed feedback
- Speed feedback re-creates conventional speed stability, causes washout/reversal of n_z response (*autothrottle off*)
- additional \dot{v} feedback needed to add phugoid damping
- *There is no flight path command reference, and no long term path tracking capability (without thrust re- trim)*
- Additional design complications not shown:
 - n_z corrections needed to avoid divergence
 - algorithm reconfiguration for Take Off & Landing
- Multiple speed references in C*U and autothrottle can cause control divergence

FLIGHT PATH ANGLE BASED FBW MANUAL CONTROL

- Since $FPA = \dot{h}/V$, \dot{h} command concept can easily be reconfigured into FPA concept with same basic HQ; then
 - F/g easily scaled for desired sensitivity and authority
- Direct FPA control facilitates precision maneuvering and reduces workload
- Use of the FPA control strategy facilitates
 - uniform HQ throughout flight envelope
 - implementation of envelope protection features : n_z , α , speed
- FPA control concept is inherently compatibility with HUD and energy control strategy

PITCH ATTITUDE VERSUS FPA CONTROL ALGORITHM PERFORMANCE

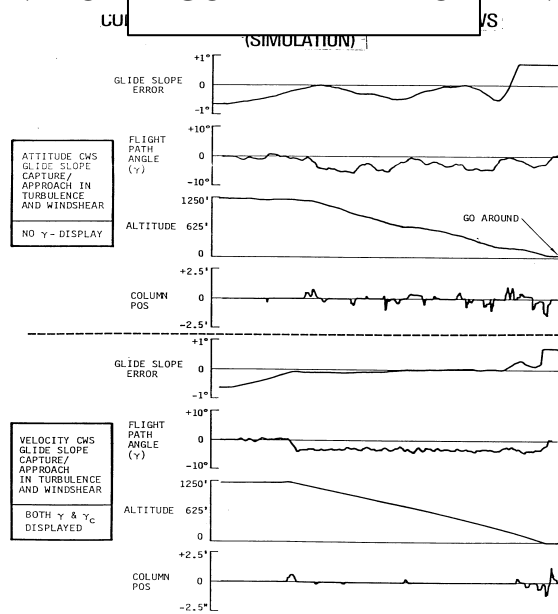
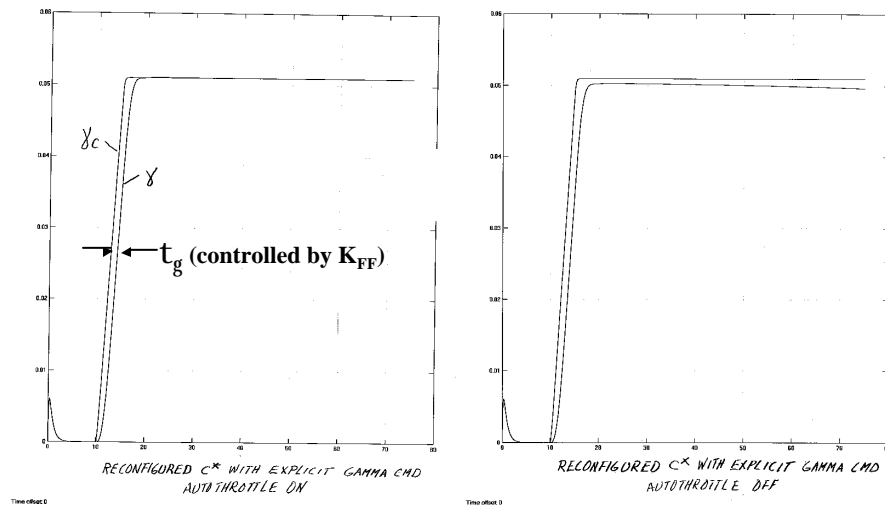
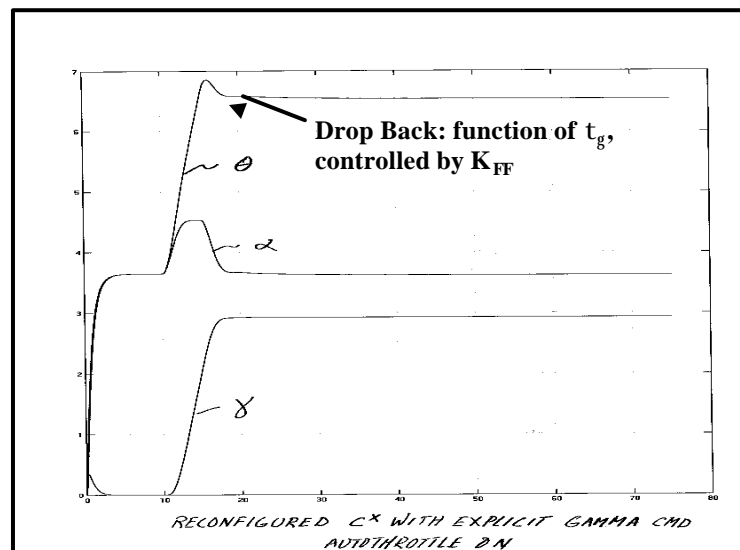


FIGURE 11. COMPARISON OF ATTITUDE AND VELOCITY CUE FORMATIONS

TYPICAL RESPONSES FPA-CMD ALGORITHM



TYPICAL RESPONSES FPA-CMD ALGORITHM

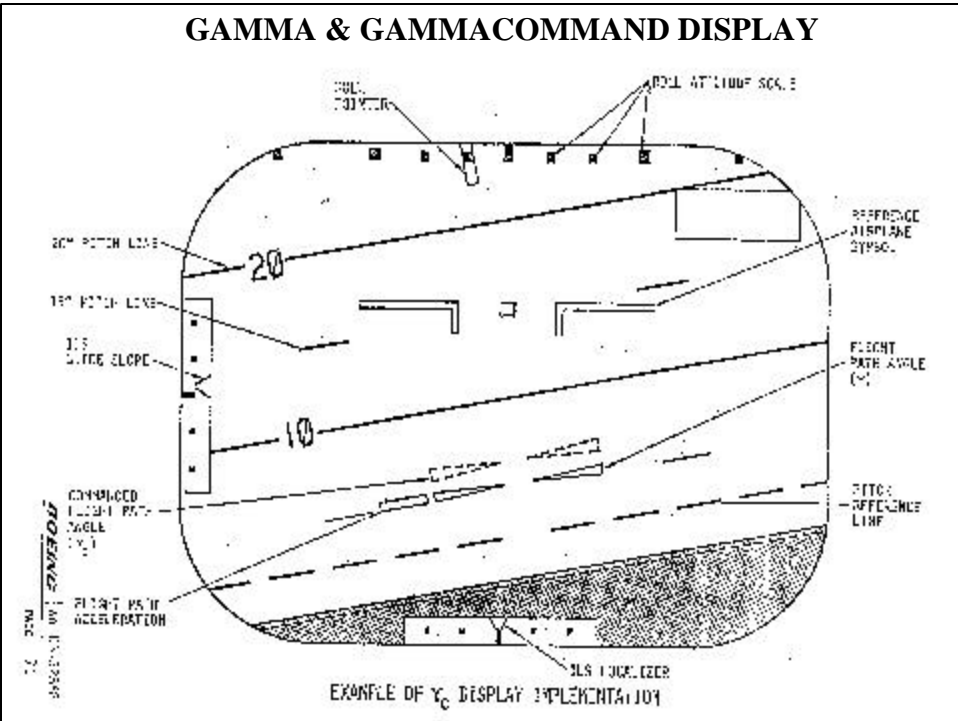


FBW PRIMARY FLIGHT DISPLAYS

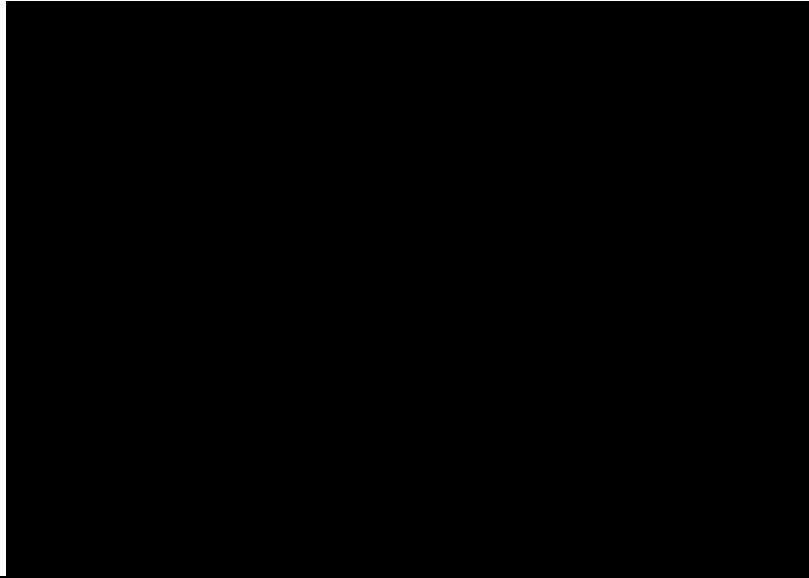
- If FBW control strategy is traditional (attitude short term), then primary flight displays can be traditional as well
- If an advanced control algorithm is used, including envelope protection features, then the PFD need to be suitably adapted

FOR EXAMPLE:

- **Traditionally, the flight path is controlled by iterative adjustment of attitude**
- **It is possible to control flight path more directly by providing flight path response lead-information on the display:**
 - **quicken flight path angle display (Flight Dynamics HUD)**
 - **display of reference FPA command (NASA/Boeing TCV)**
 - **allows the pilot to control “K/S”: reduces PIO risk**



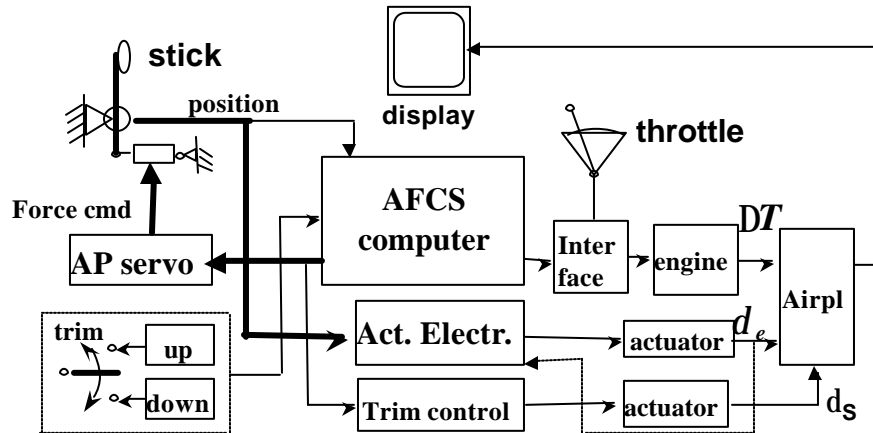
GAMMA RESPONSE LAG COMPENSATION



FEEL SYSTEMS

- tactile “feel” feedback force provides a sense of “metering”
- in classical airplane feel force is affected by surface deflection/ trim, angle of attack, dynamic pressure
- classical feel force characteristics (F_c/N_z ; F_c/DV ; F_w/d_w) aid the pilot in safely controlling/trimming the airplane
- *powered controls* destroy the natural force feedback; artificial feel system (force gradient = $f(qbar, \text{Stab Pos})$) restores basic “feel” and safety
- *FBW control computer can provide the essential safety features; eliminates need for complex/heavy feel and stick shaker system*
- *a passive linear feel spring is then sufficient to achieve good HQ at all flight conditions - may need automatic trim*

BACK DRIVEN SYSTEMS

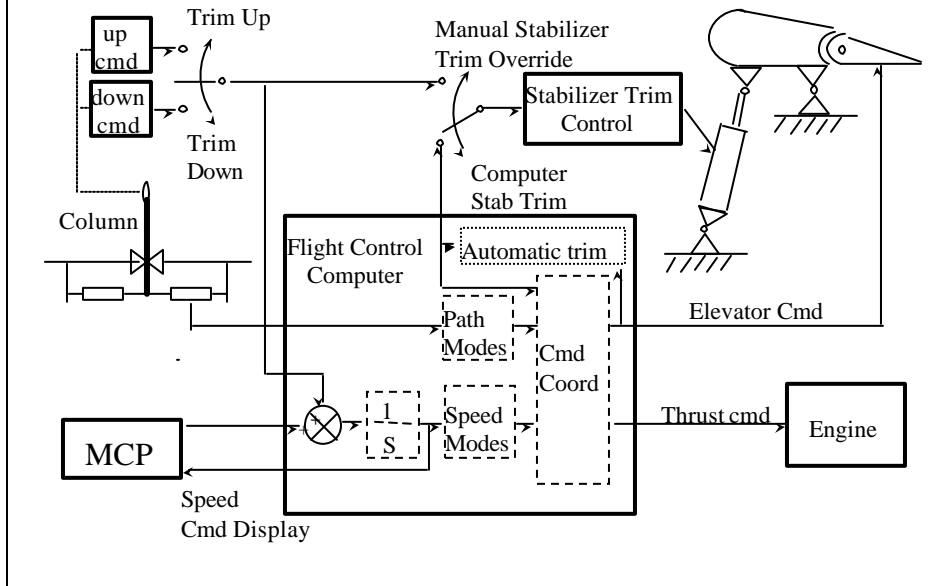


- control surface driven parallel to pilot controller
- computer drives feel system- not the airplane!
- usable only for simple proportional commands without S/CAS

FBW PITCH TRIM SYSTEM

- manual pitch trim capability is required for take off
- automatic trim needed for systems that do not schedule stick force directly proportional to elevator deflection
 - Example: stick commands n_z , $F_s = K * d_s$
 - problems:
 - if system does not exhibit speed stability, *speed divergence will result in trim divergence*;
 - need envelope protection (equivalent safety);
 - concept of “trim speed” lost
 - automatic speed control almost a necessity
 - if system *does* exhibit speed stability, the same reference speed command should be used for manual “pitch trim” and automatic speed control

SPEED TRIM / STABILIZER TRIM CONTROL



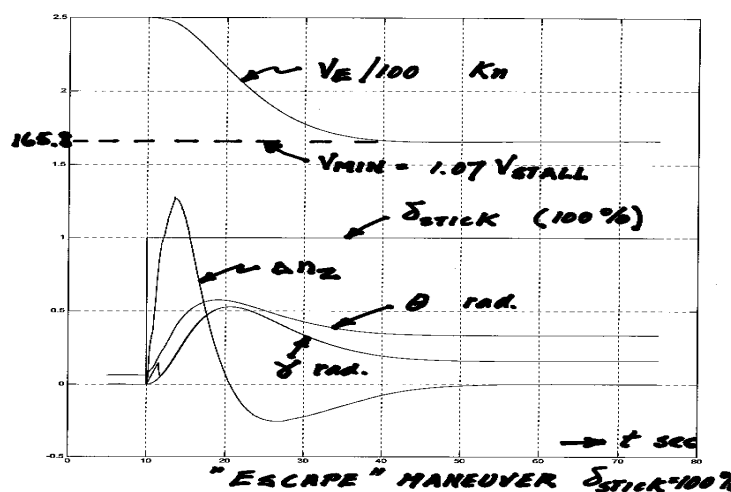
ENVELOPE PROTECTION

- **Objectives:**
 - **prevent stall (observe alpha limit)**
 - need for stalling capability not identified!
 - **prevent overstressing of airframe (limit n_z)**
 - **provide safe maneuverability up to airplane performance limit (stay within speed envelope)**
- **n_z control authority limit simply and effectively implementable in software: full stick = n_z -limit command**
 - $V < 1.58 V_{\text{stall}}$: $n_z\text{-limit}^+ = \{1 - V^2 / (V_{\text{stall}})^2\}$
 - $V > 1.58 V_{\text{stall}}$: $n_z\text{-limit}^+ = \text{structural limit}$
 - $n_z\text{-limit}^- = -.5$ Flaps Up; $n_z\text{-limit}^- = 0$ Flaps Down
 - $\ddot{h}_{\text{cmd}}\text{-limit} = N_z\text{-limit} * g$; $\dot{g}\text{-limit} = \ddot{h}_{\text{cmd}}\text{-limit} / V$

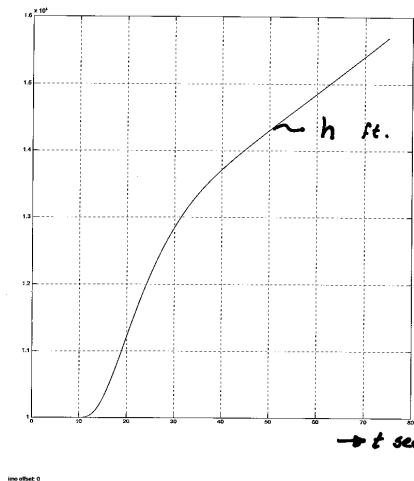
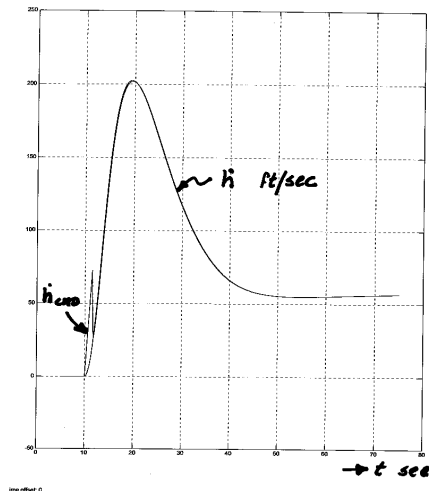
ENVELOPE PROTECTION (cont'd)

- speed envelope safeguards: simplest in software, using integrated flight path and speed control strategy:
 - partial stick, thrust not at limit: command n_z ($V = \text{constant}$)
 - partial stick, thrust at limit or constant: command n_z short term, ΔV long term (normal speed stability)
 - full stick, thrust not at limit: command n_z -limit
 - full stick with thrust at limit: command speed change, limited to speed margin relative to speed envelope
 - manual trimsets reference speed, auto elevator trim
- using above strategy, stall protection is implicit; explicit algorithm avoided

COLLISION AVOIDANCE MANEUVER HITTING N_z , ALPHA AND SPEED LIMITS



COLLISION AVOIDANCE MANEUVER HITTING N_z , ALPHA AND SPEED LIMITS



MYTHS

- Simple angle of attack (AOA) command concept is “classical” and therefore “best”
 - evaluation on HSCT program proved notion wrong
 - AOA (constant speed) = n_z = FPA-rate
- Pitch up to stick shaker yields max vertical performance (e.g. windshear escape, collision avoidance maneuver):
 - control to alpha near stall is very difficult and precarious
 - constant AOA \neq constant n_z
- Envelope protection reduces pilot control authority and available performance (Ron Rogers: ALPA paper)
 - pilot evaluation showed otherwise (“Hard/Soft Limiting”)
 - pilot cannot effectively extract max performance while observing alpha, n_z , speed limits; FBW computer can!

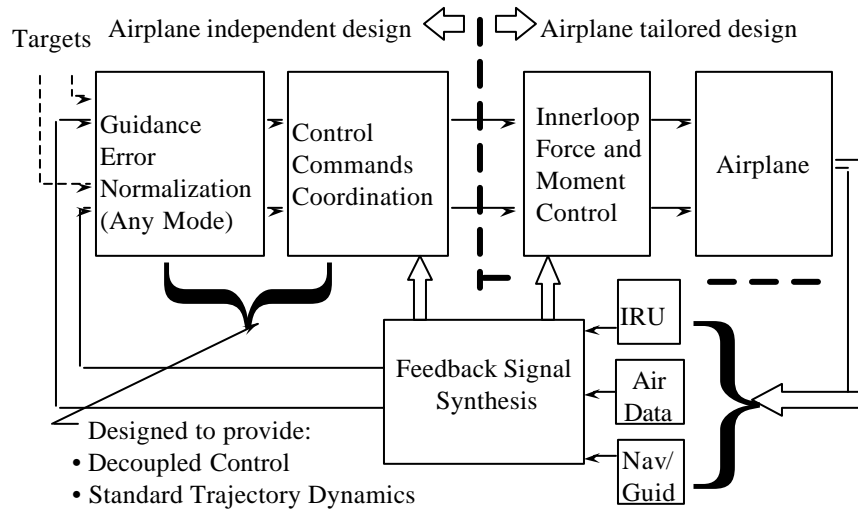
FBW DESIGN PITFALLS

- **“minimum change” strategy: old design converted to FBW**
 - **unnecessary complex / inefficient hardware architecture**
 - **“Baggage” - held over from previous generation design**
- **poor design integration / execution**
 - **incompatibility of FBW manual and automatic modes**
 - **multiple speed control references in FBW and autothrottle**
- **flawed concepts**
 - **poor choice or design of control algorithm**
 - **automatic stabilizer trim on pitch demand - unlike pilot, who trims for zero force at desired speed**
 - **flight envelope protection**
 - **incomplete**
 - **angle of attack limiting with thrust**
- **system elements the designer cannot explain**
- **complex logic; undefined/untested system states or modes**

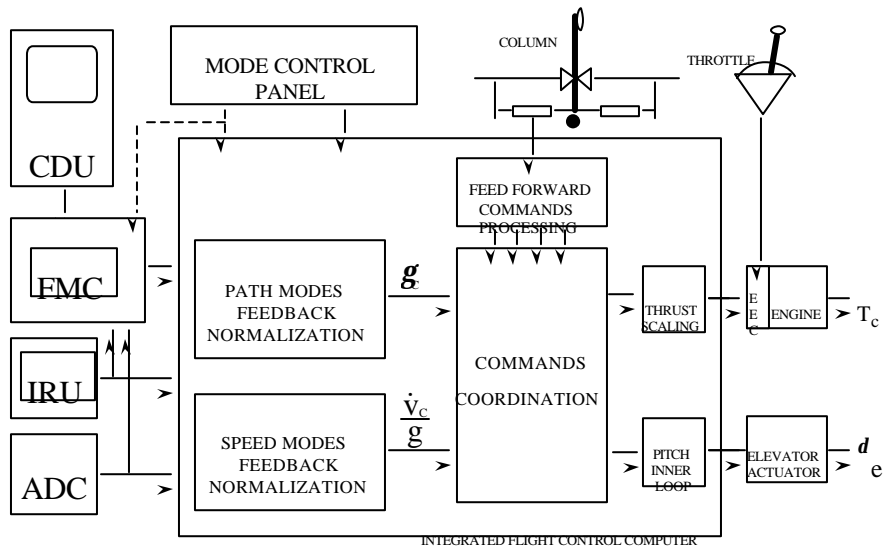
FBW DESIGN PITFALLS (cont'd)

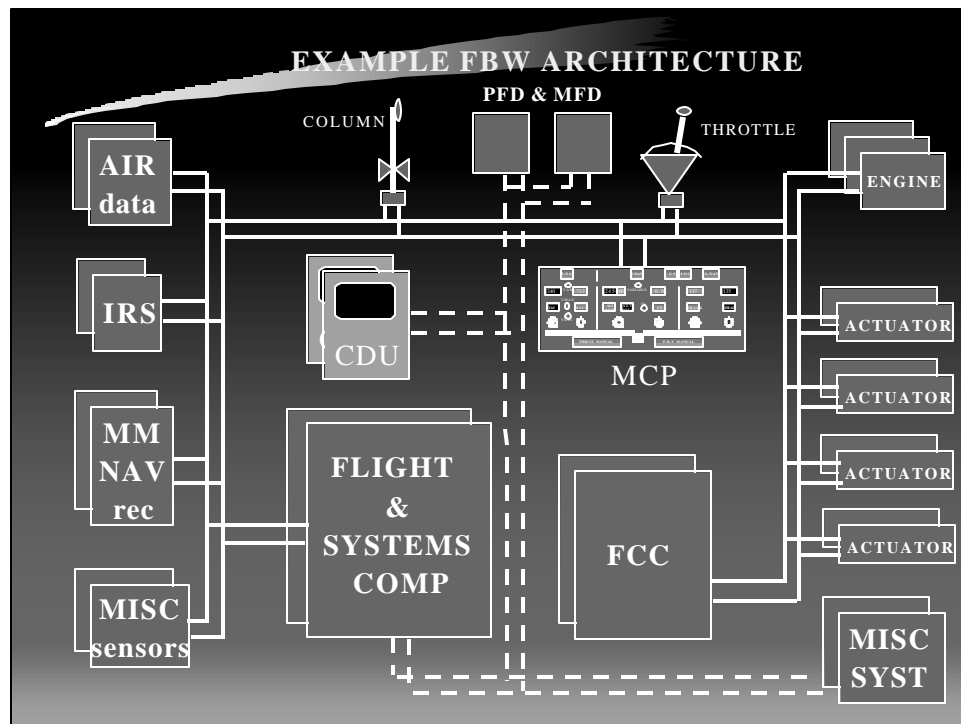
- **PIO (Airplane Pilot Coupling) susceptibility due to**
 - **actuator rate & position saturation caused by**
 - **dynamic elements (e.g. lead-lag) in the forward loop**
 - **mismatch controller input and actuator authority**
 - **apparent “disconnect” - extreme airplane response lag, e.g. FPA, Altitude, Speed control tasks - low speed**
 - **excessive airplane responsiveness - high speed**
 - **severe non-linear (surprise) airplane response**
 - **unsuitable loop closure displays**
 - **integrator wind-up**
 - **discontinuity in**
 - **controller input sensitivity**
 - **feel force gradient**
 - **algorithm gains (mode switching)**

GENERALIZED CONTROL CONCEPT



FUNCTIONALLY INTEGRATED FBW MANUAL AND AFCS ARCHITECTURE





FBW FUNCTIONAL RELIABILITY STRATEGIES

- **REQUIREMENT:** loss of function probability $<10^{-9}$ / fl hr
 - failure probability of hardware components and LR Us are orders of magnitude too high to meet above reliability with single string - *Need Functional Redundancy*
 - loss of function can occur due to
 - random hardware failure
 - design error (specification; implementation)
 - crew error (exceeding envelope)
 - hardware and software strategies to meet requirements
 - similar to Fail-Op Autoland; difference: *exposure time*
 - parallel/dissimilar hardware & software - no HQ degr
 - reversion to simpler backup mode(s) - graceful degradation of HQ, performance & protection
 - Fault Detection, Identification and Reconfiguration
- More details in Automatic Flight Controls Course*

CERTIFICATION REQUIREMENTS

- **Same general safety requirements as for mechanical flight control systems apply:**
 - **Some requirements referring to mechanical control system implementation may not be appropriate**
 - **Special Requirements may be issued**
 - **application of new technologies**
 - **new functionality**

FBW SPECIAL CONDITION REQUIREMENTS

- **Handling Qualities**
 - **static longitudinal stability (25.173); “speed stability”**
 - **static lateral directional stability (25.177)**
 - **sidestick controller: forces; controller interconnect; cross talk**
- **control surface position awareness / indication**
- **out of trim characteristics (25.255); mistrim maneuvering**
- **effect of EFCS on structure**
- **fail safe control surface for flutter prevention**
- **effect of spurious signals (HIRF/Lightning) on**
 - **actuator command and response**
 - **mode change**
- **Equivalent safety -envelope protection**

FBW SPECIAL CONDITIONS IMPOSED ON PREVIOUS DESIGNS

Flight Envelope Protection:

-)General Limiting Requirements**
-)Angle-of-Attack Limiting**
-)Normal Load Factor (g) Limiting**
-)High Speed Limiting**
-)Pitch and Roll Limiting**

Side Stick Controllers:

-)Pilot Strength**
-)Pilot Coupling**
-)Pilot Control**

DESIGN SAFETY ASSURANCE PROCESS

- **SAE 4761 provides guidance for airplane systems safety assessment**
 - **Functional Hazard Assessment (FHA)**
 - **Fault Tree Analyses (FTA)**
 - **Common Mode Analyses**
 - **Specific Risk Analyses**
- **DO-178B Software Considerations in Airborne Systems and Equipment Certification - distinguishes 5 levels of software correctness assurance:**
 - **A for errors that may cause a catastrophic event**
 - **B for errors that may cause a severe-major event**
 - **C for errors that may cause a major event**
 - **D for errors that may cause a minor event**
 - **E for errors without a safety impact**
- **provides guidelines for conducting verification process**

SAE & RTCA GUIDANCE MATERIALS ON AUTOMATION

- **SAE ARP 4761** **Safety Assessment**
- **SAE ARP 4754** **Certification Considerations for Highly Integrated or Complex Aircraft Systems**
- **RTCA DO-160C** **Protection of Aircraft Electrical, Electronic Systems Against the Indirect Effect of Lightning**
- **RTCA DO-178B** **Software Considerations in Airborne Systems and Equipment Certification**
- **SAE ARP 4101/1** **Flight Envelope Awareness / Protection**

QUESTIONS OR COMMENTS

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